Application of Mathematical Modeling in Potentially Survivable Blast Threats in Military Vehicles

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ABSTRACT

Crew injuries and fatalities of military personnel in vehicles are a significant concern in the U.S operations in Iraq and Afghanistan. And the predominant cause is Improvised Explosive Device (IED) attacks on vehicles [source: www.iCasualties.org]. A computational model using MADYMO, a mathematical dynamics modeling software, which utilizes lumped parameter, rigid body and finite element methodologies, was developed for the study. MADYMO simulations were performed with the correlated MADYMO model to understand the occupant injury values under the influence of various generic mine blast pulses and seat system energy management design parameters. In addition, the concepts of Effective G and Delta V to relate structural performance to occupant injury risk were investigated.

1. INTRODUCTION

Typically, a vehicle's structure absorbs some of the blast induced energy through plastic deformation of metal but most of it is transferred to the vehicle, generating a high impulse and momentum change. In vehicle designs, where seats are integrated into the floor and an occupant's feet are in contact with the floor and toe pan, the possibility of serious injury risk to lower legs, lumbar and cervical spine exists due to the direct blast load path of the shock wave propagation. Blast effects under a vehicle due to mine or an IED are categorized into local effects, global effects, drop down effects and subsequent effects. The local effects immediately following the blast event usually generate very high, short duration accelerations on the underbody and floor of a vehicle. The global effect occurs when the vehicle undergoes rigid body motion, primarily in the vertical direction after the initial local effects subside. The drop-down effects are due to the vehicle slam down after reaching its peak displacement in the vertical direction. The subsequent effects are due to vehicle rollover and other types of crashes [NATO/RTO HFM-090/TG-25; referred to as the NATO report from here on]. From the laboratory tests, it was observed that the blast acceleration pulses ranged from 100g with a time duration of 10-ms to 350g with a time duration of 5-ms for the initial blast phase; and a range of 20g with a time duration of 30-ms to 60g with a 15-ms time duration for the drop-down phase (see Figure 1). These blast and drop-down shock wave signatures are fairly representative of generic heavy trucks.

In the study, the blast event acceleration profiles were considered for occupant injury risk evaluation at a sub-

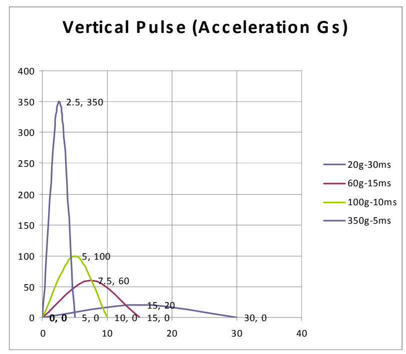

Figure 1: Generic Mine Blast Pulses

system level using the vertical drop tower MADYMO math-based model. The floor, seat and restraints sub-systems were modeled to simulate crew compartment interactions during the highly transient event. The analysis that follows considers only the unidirectional vertical loading condition; the off-axis and rotational components were not considered.

2. CREW INJURY CRITERIA AND TOLERANCE

Crew injuries due to mine blast effects on an underbody of a vehicle are primarily caused in lower legs, thoraco-lumbar spine, neck, head and internal organs. The main injury mechanisms are: (a) elastic – compression and tension of body under loading if elastic tolerances are exceeded, (b) viscous – when fluid matter is involved in the body region and mechanical responses are rate dependent and finally, (c) inertial – acceleration type of loading where internal organs and tissues are excessively deformed beyond tolerance limits. The injury mechanism is based on time duration dependent acceleration, force, moment or compression on the human body. Probabilistic injury risk tolerance equations and curves are developed based on test/field data analysis. According to the NATO report, a 10% injury risk using the Abbreviated Injury

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Scale (AIS) are established as compliance requirements for the blast induced crew survivability evaluations (see Table 1). The internal organ injury criteria and tolerances were not covered in the study.

AIS Code	Injury Description
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum (currently untreatable)
9	Unknown

Table 1: Abbreviated Injury Scale (AIS)

2.1 LOWER TIBIA INJURY

Laboratory and field data has shown that acceleration and compression based injuries in the lower extremity are significant under blast loading on vehicles [NATO report]. Further evidence of the warfighter trauma was reported by Stewart. When an occupant's feet are in contact with a vehicle's floor or toe pan, the load path generated by the blast shock wave directly affects the lower leg injury severity. Over the past few decades, several researchers addressed the development of injury risk equations for foot/ankle fractures as a function of tibia axial force response. The NATO report selected the Yoganandan model because of the large sample size of lower leg PMHS within a wide age range. The proposed tibia axial force tolerance value is 5.4 kN (10% risk of AIS2+).

2.2 THORACO-LUMBAR SPINE INJURY

In a study of U.S. Army non-fatal helicopter crash injuries, Shanahan, 1989, concluded that the thoraco-lumbar region is the most vulnerable portion of the spinal column when subjected to axial loading. In evaluating the existing injury criteria, NATO/RTO determined that Dynamic Response Index (DRI-z) in the vertical loading direction is a suitable compliance requirement. Latham, 1957, developed the general mechanical systems model to describe biomechanical response of human body under dynamic loading. Stech and Payne, Stech, 1969, evaluated the spring-mass mechanical systems model to understand its suitability to thoraco-lumbar spine biomechanical response. The model is a simple spring and damper system and its equation of motion is represented as:

$$\ddot{z}(t) = \ddot{\delta} + 2 \cdot \varphi \cdot \omega_n \cdot \dot{\delta} + \omega_n^2 \cdot \delta \text{ - (1)}$$

Where,

$\ddot{z}(t)$ = is the acceleration in the vertical direction measured at the position of initiation

δ = is the relative displacement of the system with $\delta = \varepsilon_1 - \varepsilon_2$; and $\delta > 0$ => compression

φ = is the damping ratio with $\varphi = \frac{c}{2 \cdot m \cdot \omega_n}$ = 0.224

ω_n = is the natural frequency with $\omega_n = \sqrt{\frac{k}{m}}$ = 52.9 rad/s

The injury metric, DRI-z, is calculated by the maximum relative displacement δ_{max} , ω_n and the acceleration due to gravity, g.

$$\text{DRI-z} = \frac{\omega_n^2}{g} \cdot \delta_{max} \text{ - (2)}$$

Stech and Payne conducted their studies and the values of φ = 0.224 and ω_n= 52.9 rad/s were selected for application to lumbar spine compression injury risk for representative air force pilots with a mean age of 27.9 years. By using data from Ruff, 1950 and Yorra, 1956, as an indication for vertebral compression fractures, Stech and Payne related the DRI-z value to an injury risk of 50% depending on the age of the population. For an average age of 27.9 years, they calculated a DRI-z of 21.3. NATO/RTO specifies a tolerance level of DRI-z = 17.7 for a 10% risk of AIS2+ spinal injury.

In addition to DRI-z discussed above, a force based criteria is also considered when associating injury risk to lumbar spine injury risk in dynamic loading conditions. In particular, aircraft industry uses a load criterion of 6700 N (1500 lb) that was proposed by Chandler, 1988. Tremblay et al, 1998, proposed a quasi-static value of 3800 N (time duration = 30 ms) and 6673 N (time duration = 0 ms) using linear interpolation between those two values for vehicular mine protection applications. These values were derived by Tremblay et al by referencing Ripple and Mundie, 1989, report.

The important aspect to be aware of when using the above criteria is that the DRI-z is a time domain dependent compression based failure criteria for vertebra fracture whereas force based criteria of 6673 N (t = 0 ms) is not time independent, single dimension pass-fail criteria. Although the NATO report specifies DRI-z as the compliance criteria for mine blast lumbar spine injury risk, the force criteria is widely used in the aircraft industry for seat designs [FAA report – Cessna Aircraft Company report to Langley Research Center, NASA]. Both the injury metrics have been covered in this study.

2.3 NECK INJURY

The neck consists of the cervical spine comprising seven vertebrae; with C1 being the top and C7 being the bottom. The axial compression loading is considered to be the dominant injury mechanism in blast events. Mertz et al, 1978, studied the neck injury phenomena in detail and developed the axial compression upper neck injury

tolerance curves. The NATO report specifies 4 kN at 0.0 ms and 1.1 kN at 30 ms as the injury criteria.

3. MADYMO MODEL DEVELOPMENT

A computational model using the Mathematical Dynamics Model (MADYMO) that utilizes lumped parameter, rigid body and finite element based methodologies was developed. The governing equations of the rigid body dynamics are the Newton-Euler equations of motion and are solved using one-step explicit numerical integration methods such as the Runge-Kutta method. The finite element method uses explicit time integration method.

A test fixture used commonly in the aerospace and aircraft industries to understand injury biomechanics due to ejection seat effects on pilots is the vertical drop tower. A similar fixture (see Figure 2) is also used in the Army laboratories to understand mine blast effects on a military vehicle underbody. The sub-system test fixture consists of floor, seat and restraints mounted on a sled carriage that is dropped from a certain height. The carriage is brought to rest by the crushing of honeycomb material. The deceleration phase of the carriage is controlled by the type of honeycomb used – cell density, wall thickness and overall thickness of honeycomb. In some instances, stacking of honeycomb material layers with different characteristics in layers produce desired complex deceleration profiles to represent various vehicle underbody impact effects due to blast loading. A MADYMO model was developed to simulate the dynamic behavior of a vertical drop test fixture (see Figure 3).

The sled carriage system was modeled as a MADYMO SYSTEM (SYSTEM 1) containing two BODIES: a body for sled carriage, and a BODY for seat/restraints system. The ATD was modeled under a different SYSTEM – SYSTEM 2. MADYMO translational joints were used to model sled carriage and seat system dynamic motion. The seat structural energy management system was represented using Kelvin spring-damper element provided in MADYMO. In the actual seat system hardware, the energy management can be achieved by bending of metal strips or crushing of tubes to dissipate the blast energy. The actuation of the energy management device was set at 4 kN at 5 mm of deflection and gradually increased for load carrying capacity.

Another important component of the seat system is the seat cushion foam. The properties of low-density, polyurethane foam were used in the analysis. The dynamic material testing data was obtained from the FAA report. The testing was conducted using a servo-hydraulic test as a speed of 30 in/s. The density of the foam was 4.4 ft/in^3; the specimen size and thickness were 7.5 in diameter and 3.25 in respectively.

Figure 2: Vertical Drop Tower (VDT) Fixture

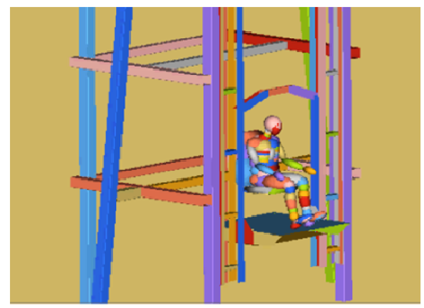

Figure 3: MADYMO Model of VDT

The input to the model was the blast loading acceleration pulse discussed previously. Typically the accelerations are measured at various locations on a vehicle during an underbody blast event: chassis, frame, doors, crew compartment, underbody, floor and seat frame. In the study, the seat mounted transducer acceleration data in the vertical direction (z) was incorporated into the MADYMO card MOTION.JOINT_ACC for the translational joint between sled carriage and the drop tower frame. The seat structure is attached to the sled carriage by means of a translational joint with the degree of freedom in the vertical direction only. The seat structural energy absorption is captured by the Kelvin spring-damper element mentioned previously.

The MADYMO Hybrid III 50th percentile ATD model [MADYMO Theory Manual for detailed description] was used in the simulations. The validated ATD model is capable of generating accelerations, compressions, forces and moments for the major body regions of interest: head, neck, thorax, lumbar, pelvis, femur and lower extremities. A standard automotive three-point seat belt was developed in the model and baseline seat belt material and retractor pull-in/out load-deflection properties were used. Contacts between ATD

model, seat belts, seat and sled carriage floor were implemented using MADYMO contact features.
In the MADYMO simulation, the sled carriage motion is reserved when compared to the actual test. As opposed to being dropped from a certain height and decelerated by honeycomb material to rest, the model is accelerated from rest to a final velocity. The sled carriage and the ATD positioned on the seat system undergo the acceleration field. Alternatively, the integral of the acceleration is termed as Delta V:

$$\int_0^t a\, dt = \text{Delta V} = V_f - V_i, \text{ - (3)}$$

Delta V is the overall change in velocity of the seat system.

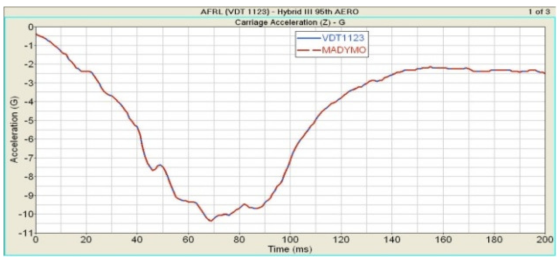

Figure 4: AFRL 10g Vertical Drop Tower Test Pulse

3.1 MADYMO MODEL CORRELATION

The MADYMO model described above was correlated to test data obtained from The Air Force Research Laboratories (AFRL), Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (RHPA). The 95th Aerospace ATD, rigid seat, lap belt and shoulder harness were used in the test. The pulse used in the test has a peak value of 10g as shown in Figure 4.

The 95th percentile Hybrid III ATD model was used in the MADYMO model instead. The correlation of important occupant injury time-history profiles is shown in Figure 5.

In general the correlation of the model to the test was good with respect to the overall shape of the curves and time duration, however in some cases, especially the lumbar load (Fz) curve, the magnitudes were different. The reason for the discrepancy is attributed to the differences in the ATDs used – aerospace versus automotive 95th percentile. The aerospace ATD has a softer pelvis than the automotive ATD.

4. PARAMETRIC STUDY

A parametric study was conducted using the correlated MADYMO model to understand effects of blast pulse severity, seat structure energy management, seat cushion foam on the 50th percentile belted ATD. The study focused on the initial blast event primarily comprising the local, global and drop down effects. The parametric study comprised the factors shown in Table 2.

Parameter	**Categories**			
Seat EA	Rigid seat	Rigid seat + EA 4000	Foam seat	Foam seat + EA 4000
Pulse	20g-30ms	60g-15ms	100g-10ms	350g-5ms
Seat cushion	Foam (low density-polyurethane)	None		

Note: *EA4000 – indicates energy management system activates at a threshold load of 4000 N.*

Table 2: Parametric Study using MADYMO Model

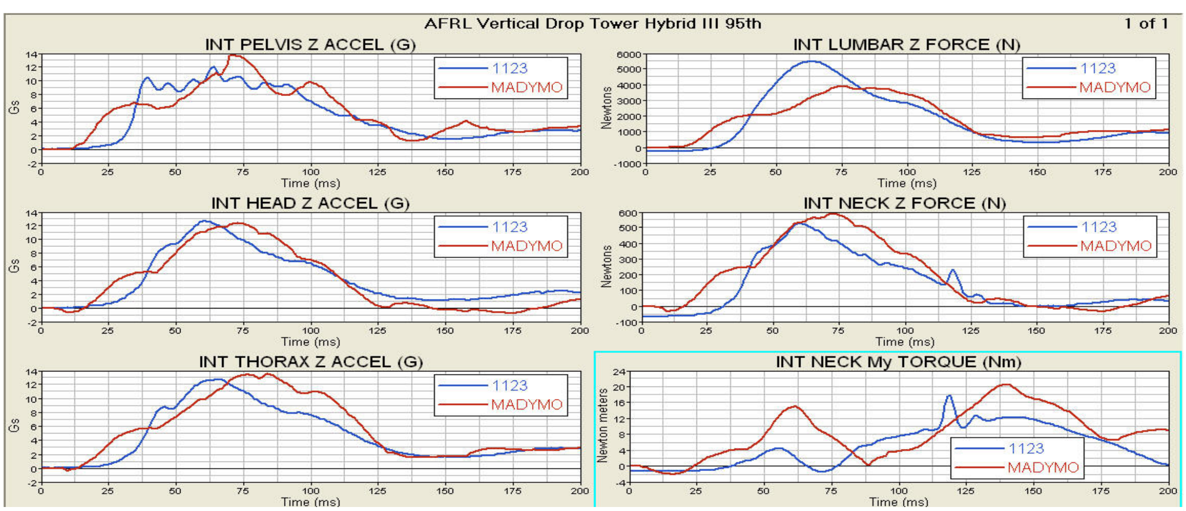

Figure 5: MADYMO correlation to AFRL 10g pulse physical test

MADYMO Vertical Drop Tower Simulation of Hybrid III 50th %ile												
				23 g	17.7	6.67 kN	60 g	700 (15ms)	4 kN	57/190 N-m	5.4 kN	254 mm
Pulse Characteristics	Eff. Gs	Delta V (m/s)	Simulation Parameters	Pelvic Gs	DRI-z	Lumbar Load Fz (N)	Chest Gs	HIC	Upper Neck Fz (N	Upper Neck Ext My (N-m)	Lower Lt. Tibia compressive load - Fz (N)	EA Stroke
20g-30ms	12.00	2.94	RS	36.14	12.56	8051.10	36.60	38.00	1664.60	-14.76	828.50	0.00
20g-30ms	12.00	2.94	RS+EA	22.48	16.21	4821.00	21.99	13.60	1003.60	-11.52	1708.10	41.10
20g-30ms	12.00	2.94	FS	16.78	12.98	3652.40	15.86	9.35	621.80	-11.12	1889.50	1.27
20g-30ms	12.00	2.94	FS+EA	12.22	13.53	3106.50	12.94	6.87	515.10	-11.80	2384.90	26.10
60g-15ms	35.98	4.41	RS	82.43	18.20	19263.00	63.10	162.49	3008.70	-24.22	1662.50	6.72
60g-15ms	35.98	4.41	RS+EA	37.93	24.15	7932.60	31.51	33.00	1411.10	-16.00	4264.20	69.90
60g-15ms	35.98	4.41	FS	30.78	19.12	5660.80	25.98	26.30	973.10	-15.50	4845.70	1.99
60g-15ms	35.98	4.41	FS+EA	26.40	20.20	4892.10	22.33	19.90	852.00	-15.50	5556.00	46.90
100g-10ms	60.00	4.90	RS	96.15	22.86	20905.00	62.56	186.44	3058.90	-32.94	1899.70	11.30
100g-10ms	60.00	4.90	RS+EA	34.10	26.37	7746.70	34.41	43.10	1481.40	-16.60	4859.20	78.20
100g-10ms	60.00	4.90	FS	37.98	20.75	6839.10	31.31	32.81	1184.30	-16.39	4845.70	0.00
100g-10ms	60.00	4.90	FS+EA	31.37	21.98	5443.50	25.00	24.70	945.60	-15.00	5706.00	53.30
350g-5ms	209.99	8.58	RS	187.18	42.37	28801.00	72.88	402.09	3282.50	-58.33	2652.30	44.80
350g-5ms	209.99	8.58	RS+EA	79.11	39.14	10078.00	47.70	99.70	2005.20	-29.30	9852.90	148.20
350g-5ms	209.99	8.58	FS	135.95	36.99	13350.00	59.99	183.38	2525.20	-41.61	10049.00	16.90
350g-5ms	209.99	8.58	FS+EA	79.03	35.74	9503.60	43.30	81.87	1686.90	-30.50	10370.00	118.20

Table 3: MADYMO simulation parametric study results

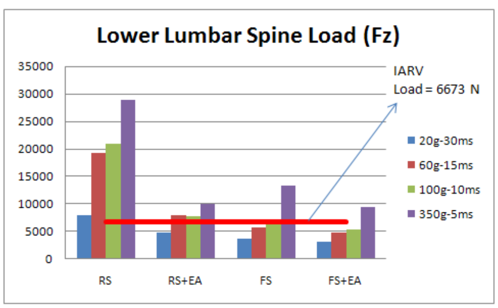

Figure 6: Lower Lumbar Spine Loads

The results of the parametric study are shown in the

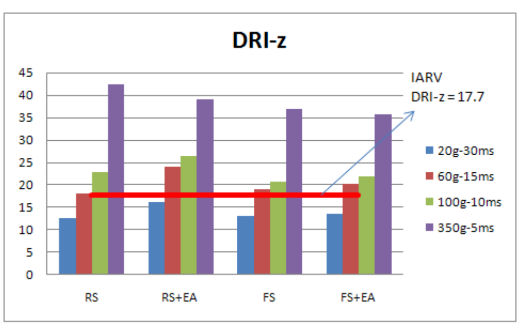

Figure 7: Calculated DRI-z values

Table 3. Several important observations were made. All the injury values noted, increased with the severity of the blast pulse; as shown in Figure 6 for example, in the case of the lower lumbar spine loads, 20g produced the lowest injury values and 350g produced the highest injury. The inclusion of injury mitigation countermeasures, whether seat structure energy management and/or seat cushion foam lowered all the primary injury values except the DRI-z. The most severe blast pulse case of peak value 350g, showed a trend of declining DRI-z with the addition of seat system countermeasures similar to the other injury values. But, in the other blast pulses cases, 20g, 60g and 100g, a slight increase was observed when the ‘rigid seat’ was replaced with ‘rigid seat+EA4000’; similar trend was observed ‘foam cushion’ was replaced with ‘foam cushion+EA4000’. It has to be also pointed out that the DRI-z values decreased slightly when the ‘rigid seat’ was replaced with the ‘foam cushion seat’ and ‘rigid seat + EA4000’ was replaced with ‘foam cushion+EA4000’. Based on this trend (see Figure 7), the inclusion of foam cushion has a slight injury reduction benefit when DRI-z is the evaluation metric. The DRI-z values were calculated using a spreadsheet program provided by AFRL that solves the 2nd order differential equation (1). The DRI-z value is based on viscous effects of the lower spine and vertebrae and the compression criteria indicates whether the body region sustains fractures or not.

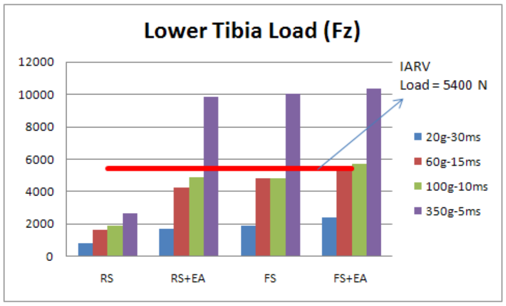

Figure 8: Left Lower Tibia Loads

Another important observation was that the lower tibia loads showed a trend reversal when energy management, both seat structure EA and foam cushion, was implemented (see Figure 8). It was influenced by the increasingly severe floor loading on the tibia as the energy management in the seat system became more effective to slow down occupant's upward motion. A simulation run was made by incorporating a block of the same foam used as seat cushion between the feet and the floor to mitigate lower extremity injury. The foam countermeasure reduced the tibia load by 5%.

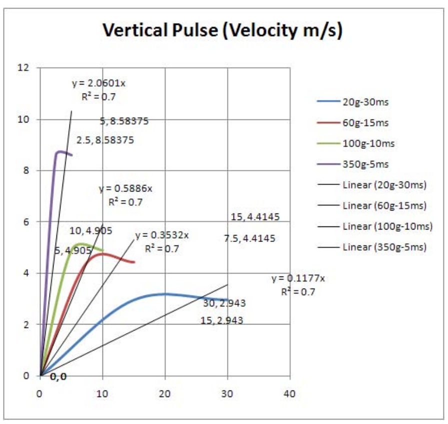

Figure 9: Calculation of Effective G

5. CONCEPT OF EFFECTIVE G

In the previous sections, discussions related to the blast pulse severity were repeatedly mentioned. Most often, blast severity is identified either with the peak magnitude, for example 20g or 350 g blast pulse, or Delta V, which is the global vehicle velocity change (Equation 3 in the previous section). It is important to understand that the human injury mechanism and tolerance for critical body regions is based on the acceleration field, which is characterized by the shape and duration of the pulse. Subsequently, it is imperative to determine a relationship between a blast pulse at the seat or floor location – if they are in close proximity to the occupant and they do not differ much in terms of overall profile – and occupant injury risk. The proposed metric for blast pulse characterization is Effective G.

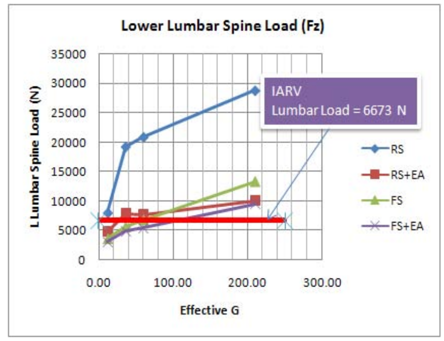

Figure 10: Effect of Effective G on Lumbar Spine

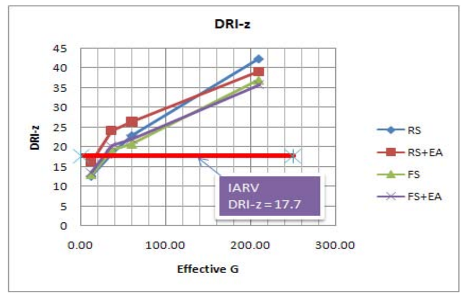

Figure 11: Effect of Effective G on DRI-z

This is simply the slope, m, of the integral of the velocity trace: y = m x + c, where c, the offset, is forced to zero to make the linear trace meaningful. As shown in Figure 9, the Effective G is calculated based on the velocity profiles of the parametric study previously described. The calculated Effective Gs and the Delta Vs are shown in columns 2 and 3 of Table 3. For instance, the 20g-30ms acceleration pulse has an Effective G of 12 and the 350g-5ms pulse has an Effective G of 210. The higher the Effective G, the higher the occupant injury risk as demonstrated by the parametric study. A directly

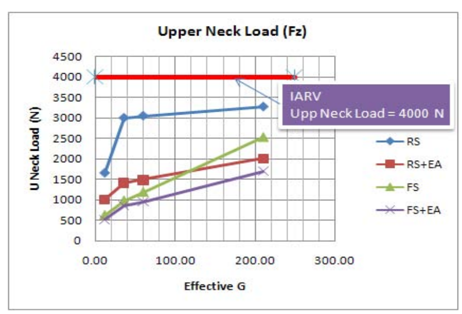

Figure 12: Effect of Effective G on Neck Load

proportional relationship between Effective G and injury values was observed as shown in Figures 10-13. A knee or inflexion point in all injury curves was detected

around Effective G of 40 and this could be due to the EA system in the seat. Considering that the DRI-z and lumbar spine loads are the dominant injury mechanisms due to load through the seat system, it is evident that the DRI-z metric is much more stringent.

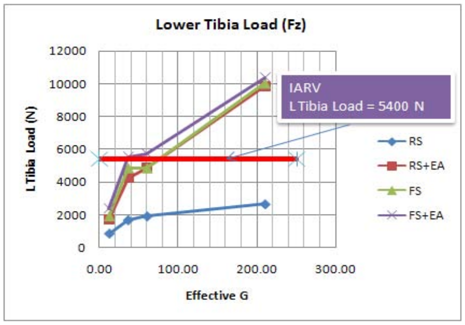

Figure 13: Effect of Effective G on Tibia Load

As shown in Figure 10, the lumbar load values exceed the IARV at a much higher Effective G of approximately, 90. In Figure 11, at approximately 30 Effective G, comparatively much lower, the DRI-z exceeds the IARV for the seat system with foam cushion+EA4000. The upper neck injury values are below IARV for all the Effective Gs and seat system configurations and they show an increasing trend with the higher Effective Gs (see Figure 12). The lower tibia loads also exhibit similar trends with respect to Effective G (see Figure 13).

The metric, Delta V, on the other hand is a cumulative quantity and although the parametric study has shown directly proportional relationship with the injury values, it can be misleading. The reason is that the actual shape and duration of the acceleration pulse which strongly influences the injury risk assessment is not considered in the causal relationship. To investigate the inconsistency further, a separate parametric study was conducted using the same validated MADYMO model described in the study. Three acceleration pulses (see Figure 14) with different magnitudes and time durations were evaluated with all the other factors constant in the simulation runs. As shown in Figure 14, the Delta V of the three pulses is the same (5 m/s), yet the crew injury values (Figures 15-17) are different. The injury values track more closely with the Effective G metric as opposed to Delta V.

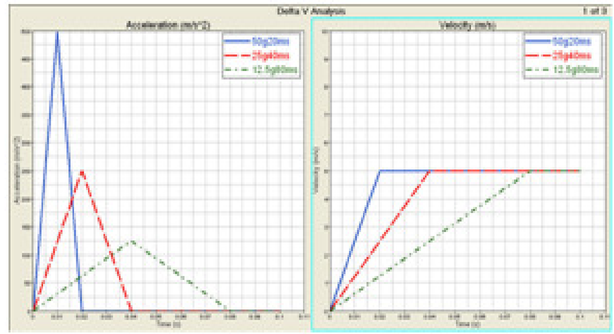

Figure 14: Different Acceleration Profiles - same Delta V

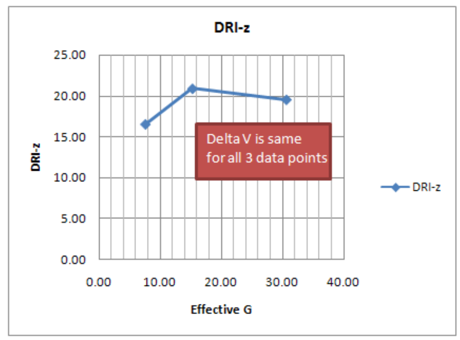

Figure 15: DRI-z Response

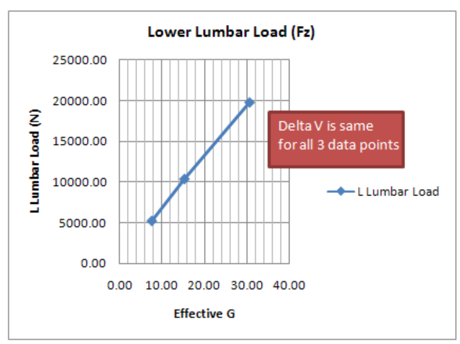

Figure 16: Lumbar Spine Response

6. CONCLUSIONS

The parametric study conducted using the MADYMO computational model indicated that all the critical crew injury values, except the lower tibia value, were lowered with the implementation of seat system energy management. By adding the toe pan foam padding, the tibia loads were reduced by 5%. The DRI-z

value showed slight improvement only for the most severe blast pulse of 350g; addition of the seat cushion foam reduced the DRI-z slightly. The metric that establishes relationship between the vehicle structural blast performance and occupant injury was determined to be Effective G due to its directly proportional relationship with the important injury values. Delta V is a good indicator of the global vehicle effects due to the mine blast loading, but lacks the fidelity when associated with the occupant injury values which are primarily influenced by shape, magnitude and time duration of the acceleration profiles. Further analysis, in particular with various types of foam materials, seat EA force-deflection

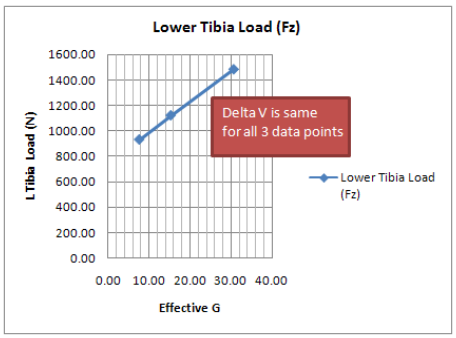

Figure 17: Lower Tibia Response

characteristics will be valuable in determining optimized parameters for improved occupant injury risk values.

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